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Economic study for an affordable small scale solar water desalination system in remote and semi-arid region

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ABSTRACT

There is an acute scarcity of potable water in many parts of the world, and especially in the Middle East region. Most of developing countries around the world endeavor to make a balance between declining fresh water supplies and the rapid demands of a rising population. Economic analysis is an essential factor influencing the decision-making in the adoption of desalination technology. This paper presents an economic and comparative evaluation study for a small scale solar powered water desalination system. An economic model has been developed and used to calculate the economic parameters. The results showed that the estimated cost of potable water produced by a solar desalination compact unit was 11 US$/m^3 and this could be reduced to 8 US$/m^3 when an evacuated tube solar collector with an area of 3 m^2 was used. It has been also proved that the cost of fresh water decreased with increasing the life-time of desalination plant. Development of small scale desalination plants based on the concept of humidification and dehumidification in a compact unit coupled with solar collectors could be considered a unique solution to water shortages in remote and semi-arid areas.

Contents

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Nomenclature

A	solar collector area (m^2)
m_y	average annual distillate output (kg)
M	annual cost of desalination system (US$)
P	capital cost (US$)
CRF	capital recovery factor
r	the interest rate (%)
n	life of the system (year) in economic study
RO	reverse osmoses
N	the annual salvage value (US$)
S	salvage value (US$)
SFF	the sinking fund factor
PC	product cost (US$)
C	cost price (US$)
HDD	humidification and dehumidification
TDS	total dissolved solids
MSF	multi stage flash

1. Introduction

Water is one of the earth's most abundant resources, covering about three-quarters of the planet's surface. Yet, there is an acute shortage of potable water in many countries, especially in Africa and the Middle East region. 97.5% of the earth's water is salt water in the oceans, with only 2.5% available as fresh water in ground water, lakes and rivers for the needs of humans and animals [1]. Tackling water scarcity must involve better and more economic ways of desalinating water. Thus, tremendous efforts are now required to make available new water resources in order to reduce the water deficit in countries which have shortages [2]. Thermal water desalination plants are mostly driven by fossil fuel sources, which add a high cost of desalination per unit cost. Therefore the need for sustainable and cost effective new water resource is currently imperative.

The use of solar energy in water desalination has become more popular and is well known, however the challenge is to utilize this solar energy in a cost effective way at reasonable costs.

Solar desalination in rural areas could have a major impact on the health, wellbeing and economic development. However, there are a number of factors that constrain implementation of large scale desalination plants in rural areas, including limitations on efficiency, intermittent power supply and inadequate infrastructure [3].

Semi-arid areas, mainly in the Middle East and northern Africa (MENA region) struggle to balance declining per capita water supplies and the demands of a rapidly rising population. In many of these countries, inadequate sources of energy and fresh water combine with inadequate financial resources. The problem of providing these areas with fresh water can be solved by transportation of water from other locations, and extraction of water from atmospheric air, but these alternatives are still expensive. Arid regions generally have a great solar energy utilization potential, as solar desalination concepts and methods are specifically suited to supply dry regions with fresh water. The key point is that efficient and environment-friendly solar energy coupled with desalination technologies could be an appropriate alternative to produce fresh water on both small and medium scales to conventional humidification and dehumidification solar desalination systems and basin solar stills with a relatively large footprint areas. Such technologies would also contribute to reduce global warming. This solution is suitable for supplying upto a half of the rural population living in arid regions that lack conventional fossil fuels [4]. Small to medium scale desalination plants utilizing the solar thermal processes and powered by solar collectors or photovoltaic (PV) cells, could be the most viable economical solution for providing freshwater to small communities in isolated arid areas with high solar irradiation and access to the sea or brackish water [5].

Cost effectiveness is a major factor in the commercialization of any desalination device. Meanwhile, the selection of the most appropriate desalination technology for a desalination device is affected by many design and economic factors, including plant size, feed water salinity (such as TDS, turbidity, temperature, heavy metals and product water quality), remoteness, availability of grid electricity, infrastructure and the type of solar technology available [6]. There are several possible combinations of desalination and solar energy technologies that could have promising water production rates in terms of economic and technological feasibility. Some combinations are more suitable for large plants, whereas others are more suitable for small-scale applications [7]. Important advances have been made in solar desalination technology, but their wide application has been restricted by relatively high capital and running costs. Until recently, solar concentrator collectors have usually been employed to distill water in compact desalination systems. Currently, it is possible to replace these collectors by more efficient evacuated tube collectors and heat pumps, which are now widely available on the market at a similar price [8]. This chapter presents an economic analysis of a small scale solar water desalination system based on the psychometric humidification and dehumidification solar water desalination system coupled with an evacuated tube solar collector.

2. Factors affecting the cost of water desalination

There are many factors to consider that could influence the cost and selection criteria of the desalination technology. The main criteria for estimating costs of small-scale desalination systems do not differ significantly from those of large-scale systems. A number of studies provided relevant information on reliable, and affordable desalting units that constitute capital investment, operational and maintenance costs, and it has been found that the desalination production cost is mainly depending on site conditions and equipment suitable for region use, especially by the specific desalination system chosen governments of countries with the greatest need [9]. Table 1 presents the most relevant parameters that affect the cost effectiveness of small to medium scale desalination plants in remote areas.

The advantage of using free and clean energy is to increase the amortization costs. However distillation with solar energy remains one of the most favorable technologies in the remote areas due to the aforementioned reasons.

A comparison between the conventional desalination system (membrane, and thermal desalination) and the renewable desalination system is presented as percentages in Table 2, which shows that, in the case of renewable energy sources, investment costs are the highest, but energy costs are the lowest. A major barrier to determine the economic cost of water desalination systems operated by renewable energy is the limited data analysis available for this purpose. Few researchers have conducted an economic analysis of their solar desalination systems in general such as Fiorenza et al. [13] for the techno-economic evaluation of a solar powered water desalination plant. Similarly Riffat and Mayere have presented generally the economics of small scale desalination system with trough solar collector [14]. Therefore in this study we will carry out a detailed

Table 1
The selection and design parameters of small-scale desalination systems for remote areas [10,11].

Parameter	Description
Weather and climatic conditions	• Solar irradiation • Wind speed • Mean annual precipitation • Ambient temperature
Technical aspects	System design to accommodate • local capabilities and needs • Reliability • Performance ratio • Efficiency
Geographical location	• Land availability • Remoteness • Acceptability to local population • Proximity to reliable brackish or seawater sources • Proximity to users
Energy	• Source dependability (conventional or renewable energy source) • Cost of energy
Feed water characteristics	• Salinity of feed water • Seawater • Brackish water • Pre-treatment and post-treatment
Financing	• Capital investments (land, plant purchase, etc.) • Operational expenditure • Maintenance and parts replacement • Amortization of investment (if applicable)
labor	• Training/education requirements • Appropriate technical skills for operation and maintenance
System infrastructure	• Access to appropriate desalination technology • Access to materials, components and supplies • Possible pumping systems for the saline water and fresh product water • Brine disposal location
Socio-cultural	• User perception of alternative practices and technologies • Local water use policy (for saline and product water) • Traditional rights and beliefs concerning water • Community's/individual's willingness to pay for the product water • Existing rights and obligations amongst members of a community

Table 2
Cost analysis comparizon between conventional and renewable energy water desalination systems [12].

Type of process	Investment costs (%)	Operational costs (%)	Energy costs (%)
Conventional (RO)	22–27	14–15	59–63
Conventional (MSF)	25–30	38–40	33–35
Renewable energy	30–90	10–30	0–10

economic analysis for the developed desalination system taking into account all the economic parameters.

3. Economics of the current water desalination situation

The cost of water produced from desalination systems using a conventional source of energy, is still much lower than those powered by renewable energy sources. But in the meantime, the costs of desalination coupled with renewable energy are steadily decreasing, whilst fossil fuel prices are rising, supplies depleting, and concerns about energy security increase.

Table 3
Type of energy supplied and water production cost [15].

Type of feed water	Type of energy	Water cost (Euro/m^3)
Brackish water	Conventional fuel	0.21–1.06
	Photovoltaic cells	4.5–10.32
	Geothermal	2
Sea water	Conventional fuel	0.35–2.70
	Wind energy	1.0–5.0
	Photovoltaic cells	3.14–12
	Solar collectors	3.5–8.0

Generally, water desalination costs have fallen over the recent years due to technical improvements and research advancements in technologies. The cost of water desalination in membrane processes varies according to the type and composition of the feed water. In the large scale conventional desalination plants, the cost of brackish water desalination was 0.27 \$/m^3 with a TDS concentration of 5000 ppm [15]. Whilst for seawater, the cost of RO desalination increased to \$0.56/m^3 for a capacity of 94,600 m^3/day [16]. Similarly in the thermal desalination processes, the cost of large systems with daily production from 91,000 m^3 to

320,000 m^3 ranges between 0.52 $/$m^3$ and 1.01 $/$m^3$ [17]. When renewable energy sources are used, the costs are much higher, and in some cases exceed 16 US$/$m^3$, due to the use of the most expensive energy supply systems. However, this cost can be counterbalanced by environmental benefits. Table 3 summarizes the cost of fresh water when the desalination systems are powered by conventional and renewable energy sources.

It can be revealed from Fig. 1 that the production cost of desalinated water is significantly affected by the capacity of the plant in both conventional and solar energy systems. However, the production cost of conventional systems is reduced only slightly with capacity when compared with the solar desalination. For production capacity ranges between 500 and 5000 m^3/day, it can be noted that the difference between the conventional and solar desalination is reduced from 3.2 to 1.9 US$/$m^3$ within the presented range of study. This value is still more than double the cost of water from the conventional system around 0.75 U$/$m^3$ [18]. Therefore, an increase in the size of solar powered desalination plants lowers the desalted water cost.

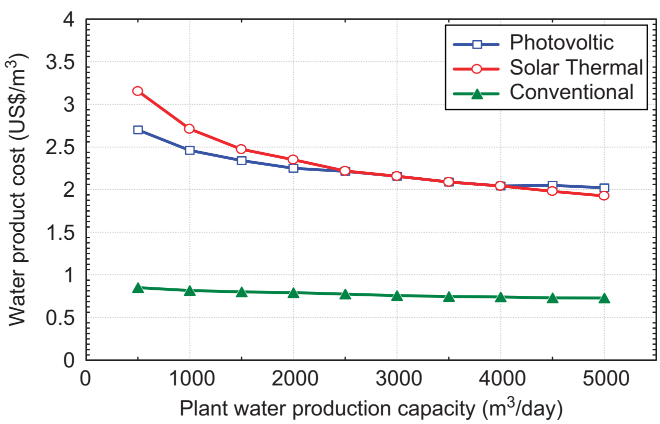

Fig. 1. Water cost as a function of plant capacity for solar and conventional systems —adapted [16].

4. Description of water desalination system

In this study, an innovative design configuration system has been proposed. The desalination system was built based on the humidification and dehumidification concept utilizing solar energy in different ways to operate the desalination unit. The humidification and dehumidification concept has been studied by many researchers for a number of years, but this innovative desalination unit has proved to have an efficient performance with high water production [19]. The desalination system is coupled with an evacuated solar collector to heat the sea water to an adequate temperature required for desalination purposes. This system employs the concept of humidification and dehumidification based on the psychometric energy process to convert the saline water into fresh water. It includes a water desalination unit, an evacuated solar collector array, a storage tank, circulation pumps, fans and ducting to handle air and auxiliary components. The desalination unit also consists of the humidification chamber, which contains an evaporation core where evaporation takes place, and the dehumidification chamber, which contains an evaporation–condensation core, where both evaporation and condensation take place for energy recycling and water production, respectively. The key innovation is the re-use of the psychometric energy created by the condensing of the moisture in the carrier gas: a small amount of thermal energy is supplied to the humidification and dehumidification process. The HDD system could be one-stage, or multiple stage system. Fig. 2 presents a schematic diagram of one-stage solar HDD process. The Evaporation Core inside the humidifier is made from a inexpensive

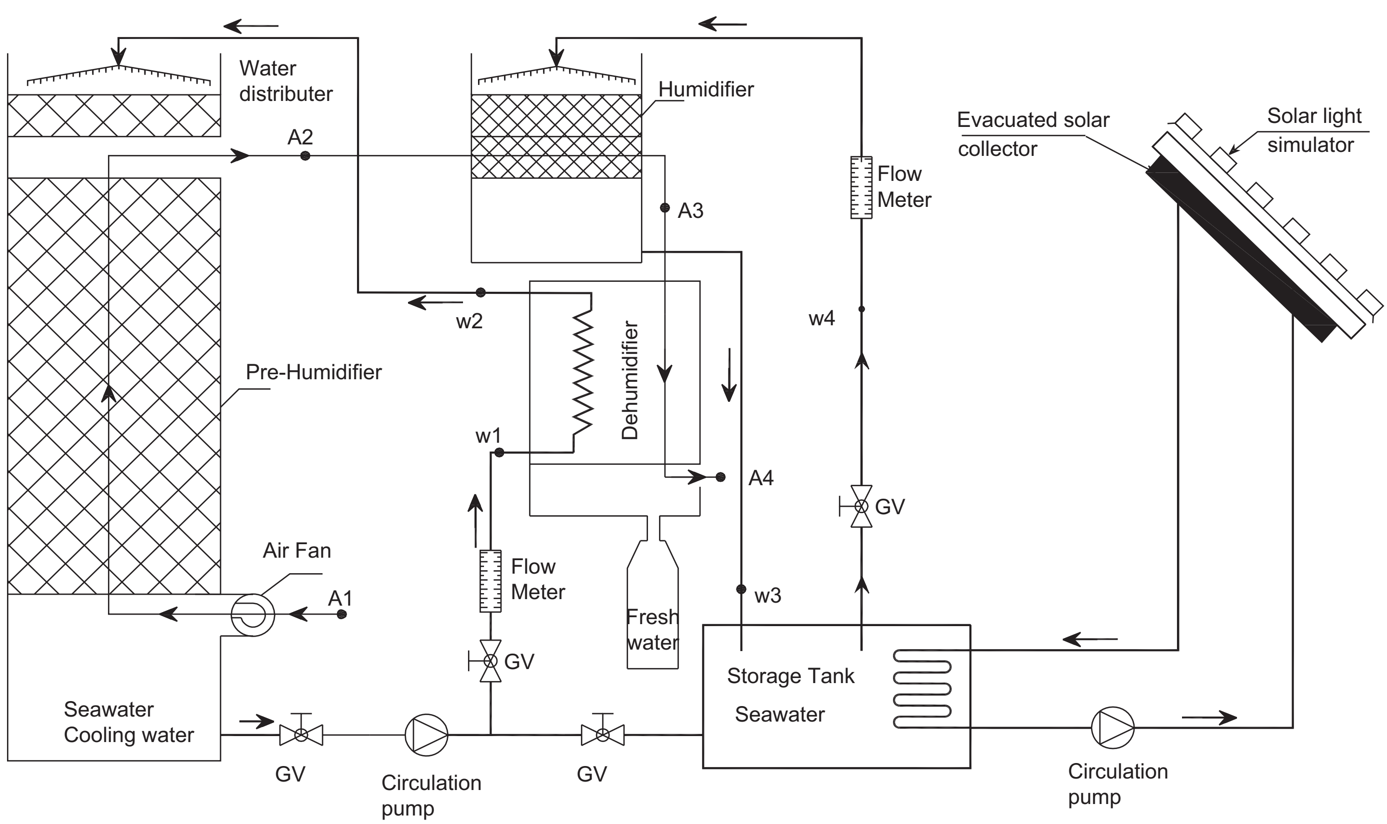

Fig. 2. Schematic diagram of desalination system [17].

packing materials of cellular paper, whilst the evaporation–condensation core contains a special designed heat exchanger, that could be replaced by membranes of a plastic to enhance heat exchanger performance and reduce the cost. The technical and experimental works of the desalination system were carried out and results published in [17].

5. Economic model

There are many methods of analyzing the economics of solar desalination systems. In this study, the method proposed by Goosen et al. [20] was adapted and applied and carried out. This study suggested that, in order to determine the unit cost of potable water produced by the desalination system, it was necessary to determine the total amount of fresh water produced and the total cost of the system, including capital, operating and maintenance costs over a certain period of time. The cost of desalination is usually expressed as a function of feed water quality (low or high salinity), desalination capacity, pre-treatment and post-treatment facilities, energy cost in addition to the salvage value, interest rate and the payback period. This model is presented as follows:

5.1. Fresh water product

It has been assumed that the desalination system is operated to produce potable water for the whole day, thus the daily collected fresh water output for the system operating over 24 h can be calculated as follows:

$$m_d = \int_{t=0}^{24\ \mathrm{h}} \dot{m}_p dt \tag{1}$$

The average annual distillate output can be calculated for 350 days using the following equation:

$$m_y = \left(\frac{1}{350}\right) \int_{i=0}^{350} m_{d,i} \tag{2}$$

It has been suggested that the plant will be out of operation for 15 days for maintenance purposes during the year.

5.2. Capital cost

The total cost of the desalination system as a function of the actual annual cost can be expressed as

$$\begin{aligned}\text{Actual annual cost (AC)} = {} & \text{The first annual cost } (M)\\ & + \text{Annual maintenance cost (AMC)}\\ & - \text{Salvage value } (N)\end{aligned} \tag{3}$$

In order to make an assessment of the cost effectiveness of the proposed system, the following cost analysis method should be carried out.

If P is the capital cost of the system and CRF is the capital recovery factor, the first annual cost of system, M, can be determined as

$$M = P \times \mathrm{CRF} \tag{4}$$

with

$$\mathrm{CRF} = \frac{r(1+r)^n}{(1+r)^n \times 1} \tag{5}$$

where r is the interest rate of the lending bank and n is the life of the system (in years). The latter is the expected lifetime of the system without loss of efficiency.

5.3. Salvage value of the system

The salvage value (S) of the system is the expected market value at the end of useful life of the desalination plant. This was considered to be 20% of the usable material cost. Hence the annual salvage value (N) of the system can be obtained in the following equation:

$$N = S \times \mathrm{SFF} \tag{6}$$

where *SFF* is the sinking fund factor

$$\mathrm{SFF} = \frac{r}{(1+r)^n \times 1} \tag{7}$$

5.4. Operational running cost

Maintenance is an essential operating cost to ensure that the system is kept in good working condition. The annual maintenance cost is the expenditure necessary to replace broken parts, and to clean and protect the system from corrosion and scaling.

The annual operating and maintenance costs (AMC) are the total yearly costs of owning and operating the desalination unit. These can include Amortization or fixed charges, operation and maintenance and parts replacement costs. In this study a fixed percentage of the first annual cost (M) has been considered, according to Goosen et al. [20].

5.5. Product cost

The product cost is represented as a function of the annual yield of the system (Y), and it can be determined as

$$\mathrm{PC} = \frac{\mathrm{AC}}{Y} \tag{8}$$

and the yield per US$ dollars (y) can be calculated as follows:

$$y = \frac{Y}{\mathrm{AC}} \tag{9}$$

5.6. Payback period

The main purpose of calculating the payback period is to determine the time point at which the capital invested in the project will be recovered by annual returns, and this can be obtained as

$$Payback\_Period = \frac{\mathrm{PC}}{\mathrm{AC}} \times Y \tag{10}$$

6. Capital cost of the distillation unit coupled with evacuated solar collector

The major cost element for a desalination unit is the capital cost. Capital cost covers the cost of equipment, auxiliary equipment, land, installation charges and water pre-treatment.

The capital cost of a water desalination system coupled with an evacuated tube solar collector to produce a potable drinking water from seawater or underground brackish water can be expressed as follows:

$$\begin{aligned}P_{Total} = {} & P_{desalination\ unit} + P_{Solar\ collector} + P_{Fan} + P_{Storaget\ tank}\\ & + P_{Pumps} + P_{Piping}\end{aligned} \tag{11}$$

The capital cost of the unit includes the initial cost of the fabrication and construction of humidifier, dehumidifier, fan, circulation pumps required for the distillation unit, insulation materials, and solar collector in addition to other required components and materials such as gasket, clamps and adhesive, and labor. It can be

calculated as

$$P_{Desalination\ unit} = P_{HU1} + P_{HU2} + P_{Condensor} + P_{SI} + P_{Fan} + P_{Pump} + P_{Piping} \quad (12)$$

It is necessary to fully insulate the desalination unit, using 150 mm mineral wool insulation. Therefore the cost of insulation can be calculated as

$$P_{SI} = A_I C_I \quad (13)$$

7. Solar panel cost

The cost of the evacuated tube solar collector depends on its area and can be calculated as:

$$P_{Solar\ collector} = A_C C_C \quad (14)$$

To study the economics of the desalination system, coupled with an evacuated solar collector, it was necessary to estimate the capital cost according to present prices. Table 4 represents breakdown of the capital cost of the desalination system components. These figures are based on prices from various suppliers.

Table 4
The cost of desalination unit with evacuated tube solar collector.

Item	Unit	Quantity	Unit cost (US$)	Total cost (US$)
Humidifier	Unit	2	63	126
Condenser	Unit	1	150	150
Insulation materials	Unit	1	20	20
Circulation pumps	Unit	3	60	180
fan	Unit	1	15	15
Storage tank stainless steel of volume 100 litre	Unit	1	100	100
Piping system and connections	Unit	1	50	50
Labour works	Unit	1	100	100
Control system	Unit	1	20	20
Plastic plates and frames	Unit	1	200	200
Solar collector	m^2	2	150	300
Sub total				1261
Overhead and profit (20%)				237
Total				**1513 US$**

8. Results and cost analysis

An economic model has been developed for small scale solar desalination plant for remote areas. This model has been programmed using Engineering Equation Solver (EES) software [21] to simulate the cost analysis of the desalination system which has been presented above and its technical characteristics with different scenarios have been published in [17]. To carry out the economic study, it is important to calculate the capacity of desalination plant under a certain climatic conditions. For this reason, the climatic condition (solar irradiation and ambient temperatures) in summer for the Middle East region has been investigated and simulated as shown in Fig. 3.

Consequently, the seasonal variations in climatic conditions have been simulated and the results showed that the average daily water production of the system in summer, spring, autumn, and winter were 28.8, 25.5, 23.7, and 15.8 kg per day, respectively, with an average annual daily production of 24 kg/day. This amount of fresh water could be sufficient for a family of five persons for drinking and cooking purposes. It has also been shown that the system could produce upto 14.5 kg/m^2.day in summer, as shown in Fig. 4. This amount of water is significantly higher than fresh water produced by an evacuated tube solar collector-coupled with four stage stills which is found to be about 6 kg/m^2/day [22].

The estimated cost per cubic meter of desalinated water was determined. It was assumed that the annual maintenance cost would be 5% of the initial capital cost, and the interest rate would be 4%. The annual operational days of the desalination system were assumed to be 350 days. The evacuated solar collector, humidifier and dehumidifier cores are the major components of the desalination system. Initially, it was assumed that the useful working life of the system was 20 years with proper maintenance, which was taken as 5% of the capital investment cost. Then different life cycles were modeled for a range of solar collector array sizes. Fig. 5 shows that the desalinated water production cost is significantly reduced when the useful life is increased and this is based on the manufacturer's recommendation for the evacuated solar collectors and other desalination unit components under given conditions.

The salvage value was considered to be 20% of the initial system cost. The economic implications of various rates of interest percentages have been modeled as a function of product cost with different solar collector areas as shown in Fig. 6. The performed calculations demonstrated that such variations had a significant

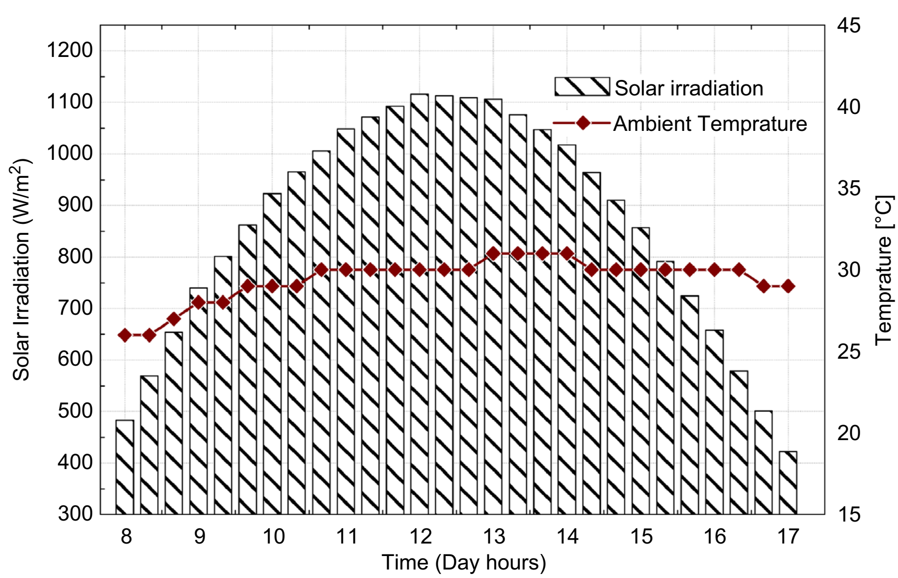

Fig. 3. Solar insolation and ambient temperature for summer in the Middle East region.

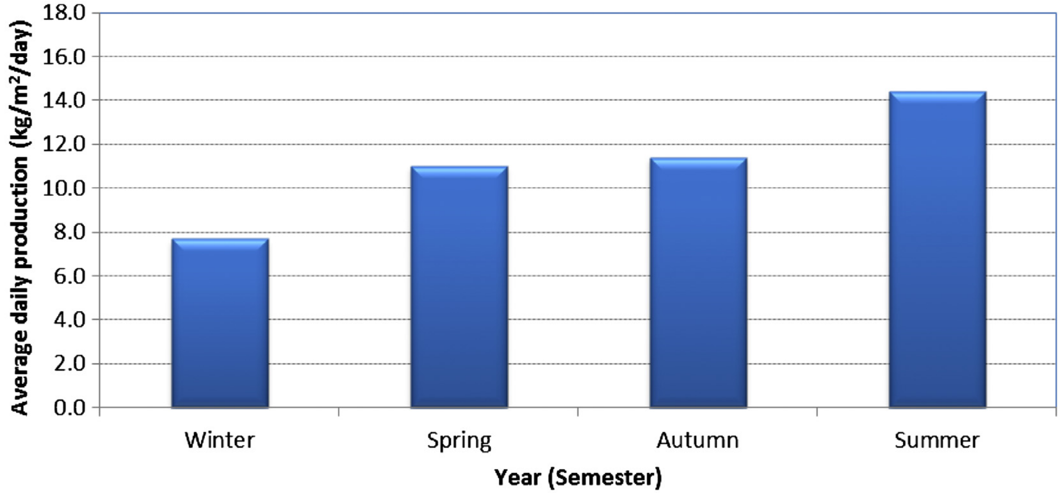

Fig. 4. Seasonal water production per solar collector unit area.

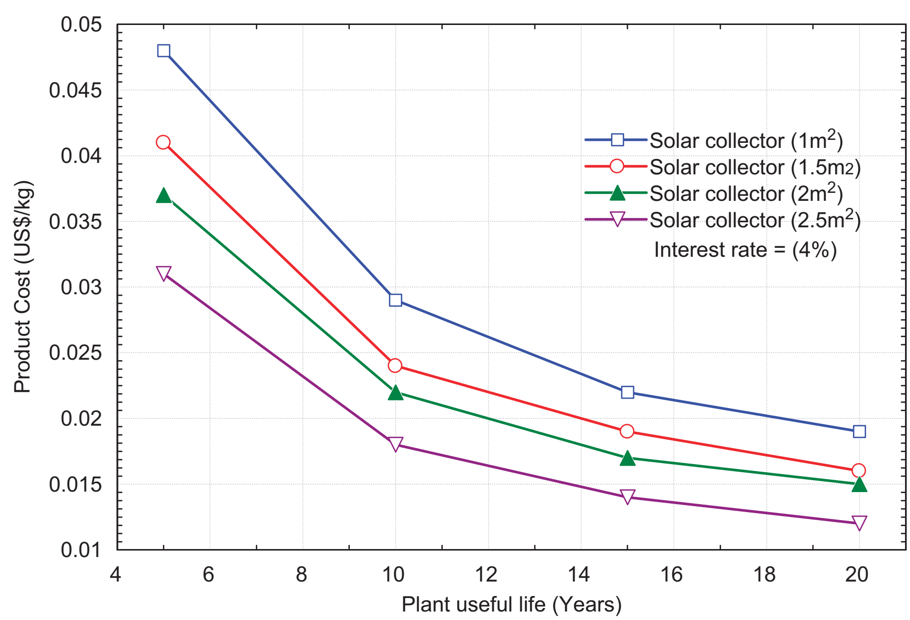

Fig. 5. Effect of plant life time on the desalination product cost.

effect on the output costs. It can be seen that the lower product cost is associated with the larger solar collector area and this due to the recent reductions in solar collector prices in the market with higher efficiency. Similarly, it can be observed that the cost per m^3 of desalinated water is 11 US$, 14 US$, 16 US$ at interest rate of 3%, 5%, 7%, respectively and this price can be further reduced through incentives to encourage the use of renewable energy such as reduction in interest on capital and exemption from taxes. From literature it is observed that running the system coupled with an evacuated solar collector array in summer can produce upto 16 kg/m^2 of fresh water per day, which is significantly higher than fresh water produced by an evacuated tube solar collector-four stage still system, at about 6 kg/m^2/day [20], with the product cost much lower compared with similar solar water desalination technologies. Currently, prices are still much higher than conventional desalination systems; however, this cost is counterbalanced by transportation alternative cost and the environmental benefits at the remote areas.

From the diagrams, it can be seen that the lowest product price of 0.011 US$/kg is achieved with a desalination plant coupled with solar collector area of 2.5 m^2 as shown in Fig. 6. Further economic analysis showed that the system could produce fresh water at price of 8 US$/$m^3$ when connected with solar collector area of 3 m^2.

Fig. 7 shows that the annual distilled water production of 10,080 l can be achieved and this can produce a useful annual energy saving of about 5460 KWh, with a payback period of 1.6 years based on the cost of bottled water.

9. Carbon dioxide emission saving

Carbon dioxide emissions are a major contributor to the greenhouse gas effect and the anthropogenic production of carbon dioxide from the burning of fossil fuels is a major cause for concern for most countries. Most countries are attempting to reduce carbon dioxide emissions through legislation and incentives for cutting emissions and promoting low carbon or renewable technologies. As apart from high capital and operating cost represented in the high share of energy consumption in the desalination process, another major concern is the excessive emission of carbon dioxide in operating desalination plants.

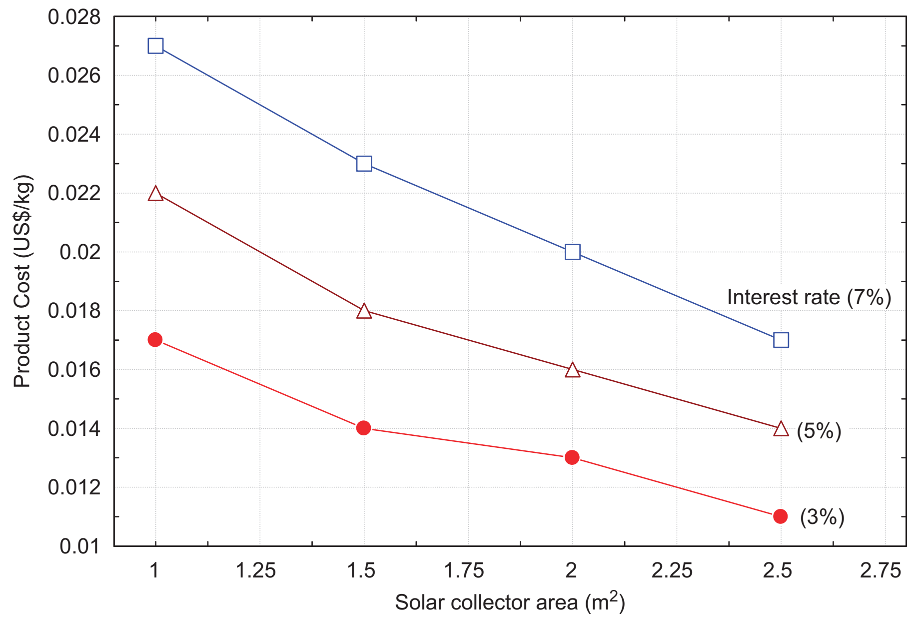

Fig. 6. Variations of product cost with the change of interest rate.

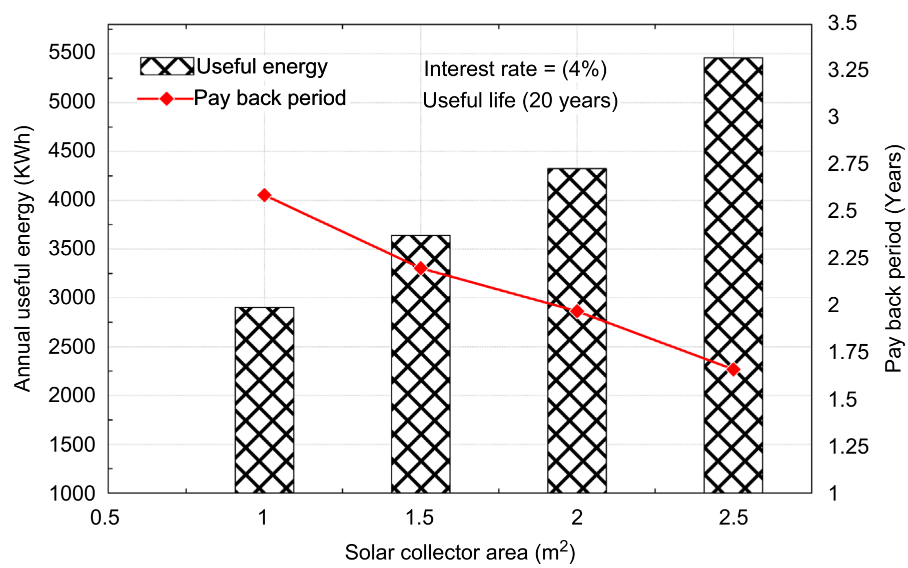

Fig. 7. Desalination system payback period and annual useful energy as a function of solar collector area.

Costs involved in increased carbon dioxide emissions include the increase in greenhouse gases in the atmosphere and environmental negative impacts on the climate global warming. For this reason such solar desalination systems would result in significantly reduced CO_2 emissions to the environment. To investigate the environmental benefit of utilizing solar energy instead of conventional source of energy, the different emission of $kgCO_2$ per unit energy resulting from the solar system operation are estimated and compared to those of a conventional electric system. The analysis was carried out based on the UK guidelines on greenhouse gas emissions. The conversion electricity to CO_2 formula is expressed as follows [23]:

$$\text{Carbon emission} = \text{electricity used per year (kWh)} \times 0.616\ (CO_2 \text{ conversion factor})$$

Carbon dioxide emission factor for the Middle East = 0.616 kg/kWh [24].

Carbon emission = 5460 × 0.616.
Carbon emission = 3663 kg CO_2/year.

The amount of carbon saving is the amount of carbon from the solar system subtracted from that of the electric system. The calculations showed that the desalination system can achieve a saving of carbon dioxide emissions upto 3663 $kgCO_2$ per year.

10. Conclusion

An economic analysis and evaluation for a small scale desalination plant operated by solar energy through an evacuated tube solar collector has been conducted. Economic analysis showed that the solar powered desalination system can achieve a 1.6 years payback period when compared with bottled water and it can achieve a saving of upto 3663 $kgCO_2$ annually when driven by

electricity from the grid. The anticipated cost of production is low since the system can be manufactured from inexpensive plastic material rather than expensive metals. It can easily be sized and scaled upto the required sizes without the need for skilled operators and complicated maintenance. Although solar powered small-scale systems tend to have higher costs per unit fresh water output, compared with conventional desalination, these costs are lower the least cost alternative which, often, is transportation by truck. In many remote areas, the reliability of delivered fuel is low, and the cost, due to fuel transportation over long distances and poor roads, is very high [11]. It can be concluded that the desalination unit powered by solar energy systems is uniquely suited to provide water and electricity in remote areas where water and electricity infrastructures are currently lacking and in semi-arid climate where solar energy is plentiful [25].

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